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Towards a better understanding of the association between motor skills and executive functions in 5- to 6-year-olds: The impact of motor task difficulty

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A B S T R A C T

Different lines of evidence suggest an association between motor skills and executive functions (EFs) in kindergarten children. Comparatively little is known about the specific nature of this relationship. In the present study, using a within-subjects design, a sample of 124 five- to six-year-old children completed 12 fine and gross motor tasks of varying nominal difficulty and three EFs tasks. We assumed that difficult motor tasks are less automated than easy motor tasks. Therefore, EFs should be involved more strongly in difficult compared to easy motor tasks. Firstly, results replicated the association between motor skills and EFs. Secondly, results provided a new and differentiated perspective on the evidence of this link. Performance on both easy and difficult fine motor tasks was significantly related to EFs. However, only performance on the difficult, but not on the easy gross motor tasks was significantly correlated with EFs. The findings demonstrate that the challenges and demands inherent in any motor task influence the magnitude of the motor–EFs link. That is, difficult (i.e., less automated) motor tasks require EFs more substantially than easy (i.e., more automated) motor tasks. Results will be discussed with regard to further candidate processes underlying the motor–EFs link.

1. Introduction

A large and growing body of literature documents a substantial relationship between motor and cognitive skills in children (van der Fels et al., 2015), adolescents (Rigoli, Piek, Kane, & Oosterlaan, 2012), adults (Ratey & Loehr, 2011), and older adults (Voelcker-Rehage, Godde, & Staudinger, 2011). For example, crawling 9-month-old infants show better performance on a visual prediction task than do non-crawling 9-month-olds, suggesting that crawling experience may foster the ability to visually predict the complex movement sequence of an object (Kubicek, Jovanovic, & Schwarzer, 2017). At the age of 5–6 years, which is the age range the present study focuses on, the interrelations of motor and cognitive skills are especially evident (Houwen, van der Veer, Visser, & Cantell, 2017; Pitchford, Papini, Outhwaite, & Gulliford, 2016). These associations suggest specific relations between various aspects of motor skills and cognitive processes, particularly concerning fine rather than gross motor skills, on the one side, and executive functions (EFs), on the other side (Livesey, Keen, Rouse, & White, 2006; Stöckel & Hughes, 2016; van der Fels et al., 2015). Beyond this relatively well-established relationship between motor skills and EFs in kindergarten children, little is known about the specific nature of this association. The present study aimed to shed light on the motor–EFs link in kindergarten children by investigating the impact of motor task difficulty on this relationship. Specifically, we addressed easy and difficult fine and gross motor tasks, and their

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specific associations with EFs.

Researchers have been examining the relationship between motor and cognitive functions for decades. Fifty years ago, Piaget stated that motor and cognitive development are closely intertwined and driven by a general biological factor. That is, the unfolding motor skills provide growing opportunities for a child to explore the environment, which in turn leads to differentiated cognitive concepts (Piaget & Inhelder, 1966). More recently, research has been focusing on the embodied cognition approach (Borghi & Cimatti, 2010; Da Rold, 2018; Oudgenoeg-Paz, Volman, & Leseman, 2012). For example, Koziol, Budding, and Chidekel (2012) describe the continuous sensorimotor interaction of a person with the environment and emphasize the cerebellum's critical role to control behaviour. In a similar vein, Ito (1993) put forward a neuropsychological argument that the manipulation and control of thoughts is not different from the manipulation and control of movements. He argued that for the cerebellum, motor actions and cognitive processes are equivalent (Ito, 1993). Although not a unitary framework, the embodied cognition perspective seeks to place cognitive processes within a sensorimotor context. While some authors highlight the body state and the importance of action for cognition in general, more radical perspectives consider cognitive processes to be limited by the nature of our body (Goldman & de Vignemont, 2009; Kiverstein & Clark, 2009). In spite of the differences between the arguments raised, the assumption that motor and cognitive skills cannot be strictly separated is at the core of all these theories.

The concept of EFs is commonly described as a set of higher-order cognitive processes necessary for goal-directed, adaptive, and flexible behaviour in novel or complex situations. EFs include the ability to suppress automatic or predominant responses (inhibition), to continuously maintain and manipulate information in working memory (updating), and to flexibly shift between multiple tasks, rules, or mental sets (shifting; Miyake et al., 2000). EFs are involved not only in mastering complex cognitive tasks (van der Fels et al., 2015) but also complex motor tasks, especially if a task is new, a fast response is required, and conditions and demands of a task change (Diamond, 2000). For example, to perform a complex motor task, children need to maintain goal-directed behaviour (Marcovitch, Boseovski, & Knapp, 2007), to control their prospective actions, to inhibit task irrelevant information, and to flexibly adapt their behaviour to current conditions. Thus, all EF components embrace higher order cognitive processes that are used to control not only cognitive processes but also motor actions.

Theoretically and empirically, there are some initial explanations for the interrelations between motor and cognitive skills. A recent study explored transactional associations among different motor and cognitive measures in 5- to 6-year-old children. The authors discuss the findings in light of two theoretical accounts, reciprocity and automaticity (Kim, Duran, Cameron, & Grissmer, 2018). Reciprocity refers to the co-development of motor and cognitive skills through the interaction with the environment. In other words, motor experience fosters the development of motor skills, which in turn facilitate interaction with the environment and thereby promote the development of higher order cognitive processes (Campos et al., 2000). The notion of automaticity proposes that motor and cognitive processes compete for the same limited attentional resources. Initial confrontation with a new task requires strong allocation of cognitive-attentional resources (Ackerman, 1988). During repeated practice, the involvement of cognitive processes such as EFs declines from "novice attention-demanding processing to skilled automatic processing" (Ackerman, 1988, p. 290). If a certain skill is automated, any new information need to be processed (Ackerman, 1988), and more attentional resources are available for executing cognitive processes (Cameron et al., 2015). Correspondingly, EFs are assumed to be no longer involved in automated motor tasks.

A more general framework for understanding the motor-cognition link in development stems from neuroimaging studies and findings from motor learning in brain injured patients (Diamond, 2000; Willingham, 1998). This neuropsychological evidence consistently showed that crucial structures for motor and cognitive skills are concomitantly activated during motor as well as cognitive tasks (Abe & Hanakawa, 2009; Diamond, 2000; Hanakawa, 2011). The dorsolateral prefrontal cortex, the cerebellum, and connecting structures, including the basal ganglia, are involved in this neural circuit. This circuit is activated when motor and cognitive skills are involved. Therefore, the output of this neural network is assumed to influence the control of both (Strick, Dum, & Fiez, 2009). As Diamond (2000) showed, activation of these brain structures is especially strong in difficult as opposed to easy tasks. Besides the involvement of sensorimotor areas and subcortical regions in easy and well-learned tasks, additional cognitive resources are recruited in difficult motor tasks (Serrien, Ivry, & Swinnen, 2007). While performing a difficult (i.e., complex) motor task, higher order cognitive resources, such as EFs, are needed to perform the task in accordance to its goals.

Although the construct task difficulty is rarely defined, it is part of almost any motor learning study. The possibilities to manipulate task difficulty (i.e., complexity) are manifold. Task difficulty can be changed, for example, by altering memory load, the number of items presented, the number of response choices, or the amount of information provided (Ackerman, 1988). Changes in these variables have an impact on the amount of attention that is required to solve the task, the precision of task performance, and the amount of time needed to complete the task (Ackerman, 1988). However, many studies in the domain of the motor-cognition link lack of an explicit operational definition of task difficulty. Guadagnoli and Lee (2004) differentiated between nominal and functional task difficulty. *Nominal task difficulty* refers to the characteristics of a task, such as its perceptual and motor performance requirements (for more details see Swinnen, Walter, Serrien, & Vandendriessche, 1992). These features make a task easier or more difficult to perform, regardless of the person who is performing it or the conditions under which the task is performed. *Functional task difficulty* describes how challenging a motor task is relative to the skill level of the person performing the task or under the conditions in which it is being performed (Guadagnoli & Lee, 2004). Both nominal and functional task difficulty influence task performance and should thus impact the recruitment of EFs resources. In the present study, we manipulated nominal task difficulty, and tried to hold functional task difficulty as constant as possible by controlling for age differences. As motor learning processes highly depend on learning occasions in interaction with the environment (e.g., Adolph, 2008), we consider age as a proxy for task practice and degree of automaticity. We assumed difficult motor tasks to be “difficult” because they are less practiced and less automated than easy motor tasks. We therefore expected that EFs are more strongly involved in difficult compared to easy motor tasks.

Reviewing the literature, there is a first hint that task difficulty may impact the magnitude of the motor–EFs link. Roebers and Kauer (2009) reported specific interrelations between various motor and EFs tasks in 7-year-old children. According to their findings, the correlations between motor and EFs tasks tended to be stronger in the first task block than in the second. This outcome indicates that with increasing task familiarity and practice, tasks became easier and the involvement of EFs decreased concomitantly.

If the challenges and demands inherent in any motor task indeed recruit EFs processes, this hypothesis should generalize to fine as well as gross motor tasks. The current evidence focuses more on fine than on gross motor skills and suggests a relatively consistent association between fine motor skills and EFs in kindergarten children (Davis, Pitchford, & Limback, 2011; Wassenberg et al., 2005). Gross motor skills, in contrast, were found to be either unrelated, or generally only weakly related to EFs (Grissmer, Grimm, Aiyer, Murrah, & Steele, 2010; Livesey et al., 2006). Although the theoretical assumptions of the motor–EFs link as well as the neuroscientific findings also account for gross motor skills, this aspect has only rarely been targeted. Especially in kindergarten children who naturally engage more in gross than in fine motor tasks, a better understanding of the relation between gross motor skills and EFs is desirable (Oberer, Gashaj, & Roebers, 2017). In the context of children’s school readiness, an early detection of risk factors for delayed motor and/or cognitive development is also of practical relevance.

1.1. The present study

Given that gross motor milestones are reached earlier in development than fine motor milestones, gross motor tasks in 5- to 6-year old children are typically less challenging compared to fine motor tasks in terms of a lower functional task difficulty. Gross motor skills in kindergarten have been practiced longer and tend to be more automated than fine motor skills. In fact, the resulting lower gross motor task difficulty may have partly led to a weaker involvement of and therefore to weaker correlations with EFs in previous studies. We hypothesised that if we increase nominal difficulty of the gross motor tasks, performance not only on fine but also on gross motor tasks should be markedly related to EFs.

Taken together, we aimed to clarify the motor–EFs link in kindergarten children by exploring how fine and gross motor tasks of varying difficulty are specifically associated with EFs. This study focussed on the hypothesis that performance on difficult (i.e., less automated) motor tasks is more strongly related to EFs than performance on easy (i.e. more automated) motor tasks, irrespective of the theoretical differentiation between fine and gross motor tasks. Overall, this study provides an innovative opportunity to advance our theoretical understanding of the interrelation between motor and cognitive development in healthy kindergarten children.

2. Method

2.1. Participants

The sample consisted of n = 124 healthy preschool children (54% girls) aged 5 to 6 years (*M* = 71 months, *SD* = 5.8, range = 60–82 months). Data from eight additional children were excluded due to reported motor disabilities (n = 4) or absence on one of the testing days (n = 4). Children were recruited from public kindergartens in the vicinity of a university town and they participated in the study only if the parents provided written consent and the children themselves gave verbal assent. According to the parents, 79% of the children were native speakers of the country’s language, 2% were bilingual, and 19% had another first language. All participants were sufficiently fluent in the country’s native language to follow task instructions.

2.2. Procedure

All participants were tested individually in a quiet room at their institution. Trained experimenters administered the tasks. Using a within-subject design, all children administered the same 15 tasks. Children were randomly assigned to four different task orders. While half of the children administered the easy task version first, the other half started with the difficult version of a specific task. The order of tasks as well as the task version executed first (easy or difficult) was counterbalanced. Within one session, either the easy or difficult version of the same task was completed. The assessments were divided into three 30-minutes sessions, taking place on three different days within three weeks. Information about the children’s health status, their physical activity level, and the familial socioeconomic status was collected using a parents’ questionnaire. The return rate was 93%.

2.3. Measurements

All participants were tested on three EFs tasks and six motor tasks, with each motor task comprising an easy and difficult version, resulting in 15 tasks overall. To design the difficult version of the motor tasks, characteristics of each easy motor task were adapted, as described below, to increase nominal task difficulty (see Guadagnoli & Lee, 2004). The operationalization of task difficulty was based on the assumption that difficult motor tasks are less automated than easy motor tasks and that EFs are more strongly involved in difficult (less automated) compared to easy (more automated) tasks (Willingham, 1998). Through the manipulation of motor task difficulty, we intended to indirectly influence the involvement of EFs. In the difficult motor tasks, we increased demands in terms of fine motor precision, manual dexterity, motor planning, whole body coordination, and balance. To master these challenges, EFs and probably other higher order cognitive processes were assumed to be required more extensively in the difficult compared to the easy task versions. If not otherwise specified, all tasks were administered according to the test manual or reference.

2.3.1. Fine motor tasks

To examine fine motor coordination, the Manual Dexterity subscale of the Movement Assessment Battery for Children-2 (M-ABC-2; Petermann, 2011) was used after adapting it, as described below. Age Band 1 (3 years, 0 months to 6 years, 11 months) comprised the Drawing Trail, Posting Coins, and Threading Beads tasks. Each of these tasks will be described below in more detail.

In the Drawing Trail task, children were asked to draw a single continuous line between two lines, without touching or crossing their boundaries. This task was completed twice with the dominant hand. The sum of errors, defined as touching or crossing the lines' boundaries, over the two trials served as dependent variable. Children completed the task with a pencil that had a conical shape at the end, either filled with polystyrene (30 g for the easy version) or steel (360 g for the difficult version; adapted from Suggate, Pufke, & Stoeger, 2016). The difficult version required higher demands on fine motor precision and adaptation in accordance with the task goals as compared to the easy task version.

In the Posting Coins task, children had to pick up 12 plastic coins, one at a time, with their dominant hand, and insert them into the slot of a box as fast as possible. This task was also done twice and the total time for the two trials to task completion served as dependent variable. For the easy version of this task, the original coins (diameter of 29 mm) and box (slot of 4×36 mm) were used. To increase the fine motor demands in the difficult version, smaller plastic coins (diameter of 18 mm) had to be inserted into a substantially thinner slot (2×20 mm).

In the Threading Beads task, children had to thread 12 beads on a lace as fast as possible. This task was conducted twice with the dominant hand, and the total time needed for the two trials served as dependent variable. While for the easy version of this task, the original cube beads (side length of 15 mm) and lace (diameter of 3 mm) were used, smaller round beads (diameter of 8 mm) had to be threaded on a thinner lace (diameter of 1 mm) in the difficult version. The round beads were not only trickier to thread because of their smaller, round shape, but it was also more challenging to find the hole of the bead to thread it.

2.3.2. Gross motor tasks

To assess whole body coordination, two speed tasks (Jumping Sideways, Moving Sideways) from the Body Coordination Test for Children (Körperkoordinationstest Für Kinder, KTK; Kiphard & Schilling, 2007) and one precision task (One-Leg-Stand) from the M-ABC-2 were used after slight adaptation. The KTK shows good test–retest reliability and acceptable validity (Iivonen, Sääkslahti, & Laukkanen, 2015).

The Jumping Sideways task consisted of a field of 60×100 cm, framed by side lines and divided into two fields by a centre line. Children were asked to jump laterally, with both feet together, over the centre line as many times as possible within 15 s. Jumps in which children stepped on one of the lines were not counted. The total number of correct jumps in two trials was used as dependent variable. While in the easy version of this task, children jumped on the floor, in the difficult version, they jumped on a soft and highly flexible polyether mat with the same dimension (thickness of 5 cm). By manipulating the material of the ground, demands on balance and whole-body coordination were increased in the difficult task version. For both tasks, children were wearing socks.

The aim of the Moving Sideways task was to move across the floor within 20 s by stepping from one wooden board to the next, transferring the first board, stepping on it, transferring the second board, and so on. To make sure that the movements were conducted sideways, we adhered two boundary lines of 50 cm distance on the floor in between which the relocations needed to be executed. The dependent variable was defined as the sum of relocations across two trials. While in the easy version of the task the two wooden boards represented squares (16×16 cm), in the difficult version, the two wooden boards were equilateral triangles with the same surface as the squares (256 cm^2). The triangular boards required more coordinative and planning processes to relocate and step on them successfully.

Balance was assessed using the One-Leg-Stand and One-Board-Balance tasks of the M-ABC-2. Children were asked to balance on one foot as long as possible (up to 30 s). For the easy version, we used the One-Leg-Stand of the M-ABC-2 (Age Band 1; 3–6 years) and for the difficult version, we used the One-Board-Balance task (Age Band 2; 7–10 years), in which children balanced on a board. To increase the reliability of the measurement, both tasks were conducted four times with the dominant foot. The total duration of balancing across the four trials served as dependent variable. For both tasks, children were wearing socks.

2.3.3. Executive functions

Three different tasks measuring EFs were included. Each of the three tasks were assumed to emphasize one of the following three core components of EFs: updating, inhibition, and shifting. The two tasks measuring mainly inhibition and updating, respectively, were computer-based and used OpenSesame (Mathôt, Schreij, & Theeuwes, 2012). These tasks were presented on a tablet computer (11.6′ screen); participants were seated approximately 60 cm from the screen.

Inhibition was assessed with a modified version of the Flanker task (Eriksen & Eriksen, 1974; Roebers & Kauer, 2009). Children were instructed to respond, as quickly and accurately as possible, to the centrally presented target—a fish—by pressing either the right or the left response button in front of them, according to the direction which the fish was facing. In order to keep the motor demands of pressing the response buttons low, children's hands remained on the response buttons during the entire task. There were two different conditions, congruent and incongruent trials. In the congruent trials, the target and the four distractors (also fish, two on each side of the target) were pointing in the same direction, whereas in the incongruent trials, the target and the flanking stimuli were pointing in opposite directions. The task consisted of a first block of 20 congruent trials and a second, critical block, which consisted of 20 congruent and 20 incongruent trials presented in randomized order. Every trial started with a fixation cross (100 ms) in the middle of the screen. Then, the stimuli array was presented for a maximum of 5000 ms or until the child responded. The inter stimuli interval varied randomly between 400 and 1400 ms. The instructions for each block were followed by a practice block, which was repeated once if the accuracy was below 60%. For further analyses, the mean reaction time of the correctly solved incongruent trials was used as dependent variable.

To assess updating, we used an adapted computer-based pictorial updating task (Jäger, Schmidt, Conzelmann, & Roebers, 2014) originally adapted from Lee, Ng, Bull, Pe, and Ho (2011). First, children were shown all the animals included in the task and were asked to name them. Children were familiar with the names of all animals. Children were then presented with a sequence of animals one at a time. Each animal was presented for 1900 ms with an inter stimuli interval of 100 ms. Children were asked to remember the last two animals and name them in the presented order as soon as a question mark appeared on the screen. Because the length of the animal sequence varied randomly across trials (minimum = 4, maximum = 7), children needed to update the animals shown last constantly.

To ensure that children understood the updating task correctly, the practice trials became increasingly difficult. Children completed six practice trials, three recalling the last, and three recalling the last two animals shown in the presented order. The task consisted of two test blocks containing five trials each, with a short break between the two blocks. For each correctly remembered animal, the child received one point. If the order of animals was also remembered correctly, the child was credited with one additional point. A maximum of three points could be achieved on each trial (30 points overall). The percentage of points (accuracy score) was used as dependent variable.

The shifting component of executive functions was measured with an adapted Advanced Dimensional Change Card Sort task (DCCS; Carlson, 2005; Hongwanishkul, Happaney, Lee, & Zelazo, 2005). Children were introduced to three boxes with a wide rectangular slot on the top. The target cards (blue square, yellow circle, and red triangle) were affixed to a box each and remained visible throughout the task. The experimenter presented ten cards with different shapes (square, circle, and triangle) and colours (blue, yellow, and red), lying in two rows in front of the boxes. We tried to minimize fine motor demands by creating cards that could be easily picked up and by using boxes with big and wide slot. Additionally, correlations with the Posting Coins tasks were estimated in the models (see below), as similar motor actions were required in those tasks. In the first block, children were asked to sort ten cards by colour into the corresponding boxes. In the second block, the children were asked to sort ten other cards by shape. In the third and critical block, children were told to sort according to shape if there was a star on the card (20% of the cards) and to sort according to colour if there was no star on the card. The third block consisted of two trials containing ten cards each, with a short break between the two trials. After the experimenter instructed and demonstrated the task, a practice block of five cards was executed. If a child made a mistake during practice, the instruction and practice block was repeated once. The overall time taken to task completion was used for further analyses.

2.4. Preliminary analyses

To obtain identical metrics, all dependent measures were z-standardized and inverted if necessary, with higher values indicating superior performance. Scores exceeding the inter-individual mean of three standard deviations (*SD*) were regarded as outliers and replaced with the value of the third *SD* (applied to 0.7% of all data points). Further preliminary analyses revealed that neither the level of maternal education nor familial socioeconomic status significantly influenced performance on motor tasks or EFs.

3. Results

We analysed data using IBM SPSS Statistics 25. Structural equation modelling was conducted with the Amos 25 software. To test the difference between two dependent correlations we used an online calculator by Lee and Preacher (2013). Model fit was assessed with the Comparative Fit Index (CFI), Tucker Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA) and Standardized Root Mean Square Residual (SRMR). According to Hu and Bentler (1999), the model fit was considered good if the CFI and TLI were greater than 0.95, the SRMR was smaller 0.08, and the RMSEA was smaller or equal 0.06. However, models were considered acceptable with CFI values greater than 0.90 and RMSEA values smaller than 0.10 (Blunch, 2008). For the results presented below,

Table 1
Descriptive Statistics of the Executive Function Tasks (N = 124).

	M	*SD*	Range	Skewness	Kurtosis
Flanker (milliseconds)	1570.67	519.70	687–3067	0.84	0.40
Animal updating (accuracy)	74.85	18.33	3.3–100	−0.84	1.07
Advanced DCCS (seconds)	62.44	18.22	31–129	0.99	1.57

Note. *M* = Mean; *SD* = Standard deviation.

Table 2
Descriptive Statistics of the Motor Tasks (N = 124).

	easy					difficult					
	M	*SD*	Range	Skewness	Kurtosis	*M*	*SD*	Range	Skewness	Kurtosis	Cohen's *d*
Fine motor tasks											
Drawing Trail (errors)	11.08	5.54	1–24	0.31	−0.42	16.51	6.90	3–37	0.59	0.28	0.87
Posting Coins (seconds)	40.46	6.13	27–62	0.89	1.41	67.71	13.57	28–119	0.82	2.11	2.59
Threading Beads (seconds)	87.44	23.11	53–150	0.99	0.73	114.71	25.45	63–221	1.06	2.08	1.12
Gross motor tasks											
Jumping Sideways (jumps)	32.27	8.34	17–57	0.60	0.04	26.82	7.79	13–49	0.55	−0.04	0.68
Moving Sideways (relocations)	29.85	6.10	15–49	0.41	0.18	25.76	6.49	8–47	0.03	0.51	0.65
Balance (seconds)	63.11	33.71	7–120	0.17	−1.17	27.64	19.26	5–97	1.42	1.81	1.29

Note. *M* = Mean; *SD* = Standard deviation. Paired-samples t-tests revealed significant differences between each easy and corresponding difficult motor task. The Cohen's *d* effect sizes are shown in the last column of this table.

the level of significance was defined as $p < .05$

3.1. Descriptive statistics

Descriptive statistics of the EFs measures are presented in Table 1. Skewness and kurtosis coefficients were rather low. Moreover, the mean accuracy score for the incongruent trials of the Flanker task was *M* = 86%. In the Advanced DCCS task, mean accuracy score for the critical block was *M* = 94%.

The descriptive statistics of the motor tasks are shown in Table 2. The skewness and kurtosis coefficients for the motor tasks were relatively low; however, two tasks showed elevated but still acceptable kurtosis coefficients, namely the difficult versions of the Posting Coins and Threading Beads tasks. Paired-samples t-tests confirmed task difficulty differences, revealing significant differences between each easy and its corresponding difficult version. The effects sizes of these differences were moderate to very high, ranging from 0.65 to 2.59.

3.2. Relationship between fine motor skills, gross motor skills, and EFs

In the next step, we examined how the included variables were associated with each other as well as with age and gender. The correlation coefficients are presented in the Appendix. Chronological age significantly correlated with all included measures (except for the difficult Posting Coins task). Therefore, subsequent analyses controlled for age. However, in this context, and as outlined in the introduction, age is more an approximation of task practice and degree of automaticity of a certain task than a control variable. As gender differences were small, inconsistent, and not our focus, data on boys and girls were combined. Partial correlations showed that the three EFs tasks were correlated with each other. Furthermore, all fine and most gross motor tasks were significantly interrelated.

To investigate if easy and difficult motor tasks are differentially related to EFs, two models were examined. While Fig. 1A shows the associations between the two easy motor factors (fine and gross motor tasks) and EFs, Fig. 1B illustrates the associations between the two difficult motor factors (fine and gross motor tasks) and EFs. The structural equation models presented in Fig. 1 provide the factor loadings (indicated by straight one-headed arrows) of each administered task on its corresponding factor (i.e., latent variable), as well as the bidirectional associations (indicated by curved double-headed arrows) of all factors. Parameters shown were adjusted for chronological age. The residual variances were allowed to correlate as follows: the residuals of all speed-based measures were correlated; namely, those of the Threading Beads and Posting Coins task as well as those of the Flanker and Advanced DCCS task. Additionally, the residuals of the Advanced DCCS and Posting Coins task were allowed to correlate because of their similarity with reference to the act of inserting cards or coins into a box.

The model shown in Fig. 1A fits acceptably well with the data: χ^2 (43, N = 124) = 30.88, $p = .099$, *CFI* = 0.94, *TLI* = 0.88, *RMSEA* = 0.057, *SRMR* = 0.056. All tasks, except the Flanker ($p = .13$) and Advanced DCCS ($p = .17$) task, loaded significantly on their corresponding constructs. Looking at the factor level, the easy fine motor factor was significantly correlated with EFs, indicating a strong relationship between performance on the easy fine motor tasks and EFs. Moreover, a non-significant correlation between the easy gross motor factor and EFs was found, suggesting that performance on the easy gross motor tasks and EFs was not significantly related. As evident from the model, the easy fine and gross motor factors were interrelated, as indicated by a correlation of as high as 0.75, suggesting that these factors overlapped substantially and shared about 56% of their variance.

The model in Fig. 1B estimated the relationship between the difficult fine and gross motor tasks and EFs. It fits the data acceptably well: χ^2 (44, N = 124) = 33.65, $p = .039$, *CFI* = 0.95, *TLI* = 0.89, *RMSEA* = 0.07, *SRMR* = 0.066. All tasks, except the difficult Balance task ($p = .062$), loaded significantly on their corresponding factors. Looking at the factor level, all three factors were significantly interrelated. The difficult gross motor factor was more strongly associated with EFs than the difficult fine motor factor. Constraining these two correlation coefficients to be equal did not significantly worsen model fit, $\Delta\chi^2 = 0.16$, $\Delta df = 1$, $p = .689$,

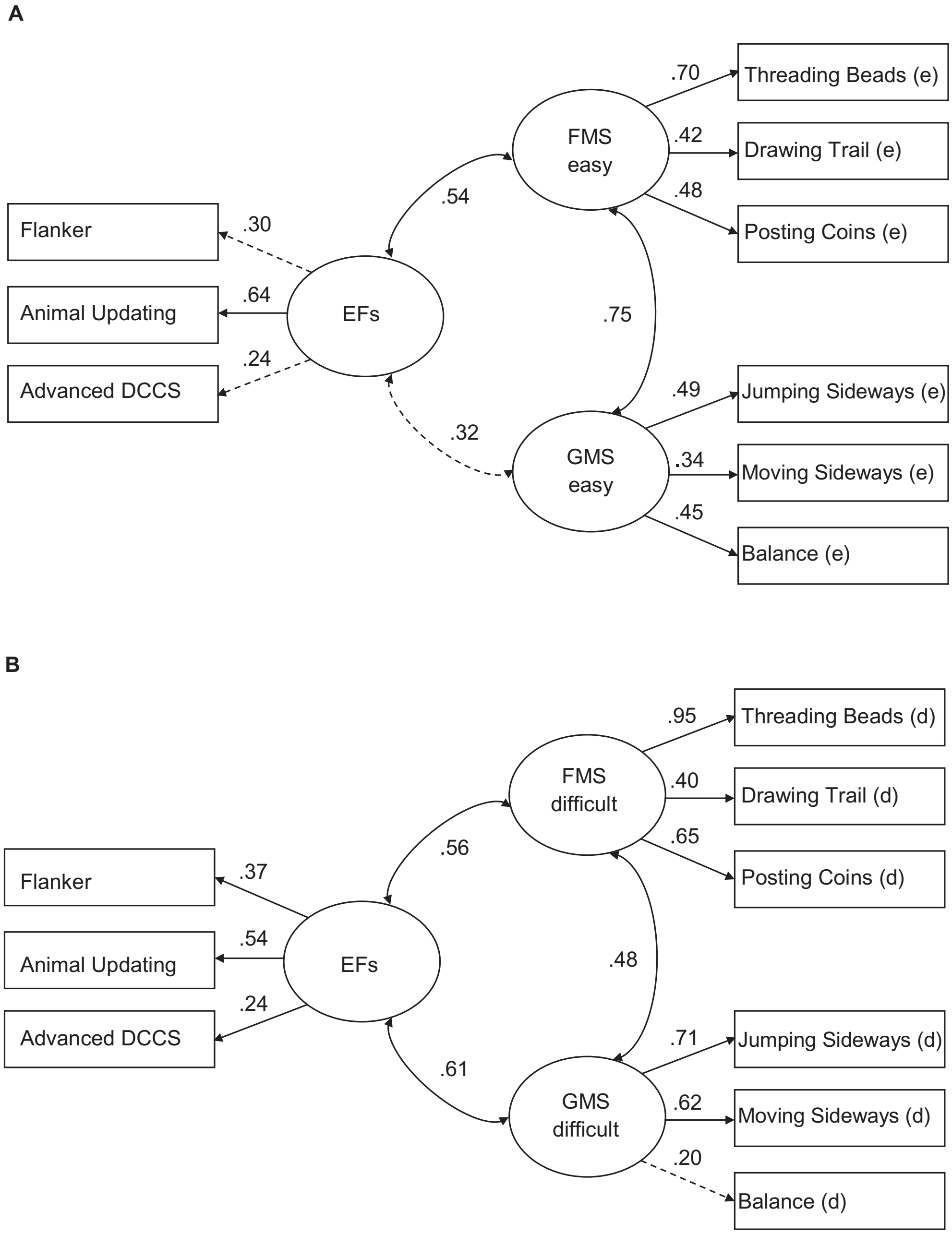

Fig. 1. Structural equation model of the associations between executive functions (EFs), easy fine motor skills (FMS) and easy gross motor skills (GMS) are presented in model A. The associations between EFs, difficult FMS and difficult GMS are shown in model B. Standardized estimates controlled for chronological age are presented. Dashed paths indicate non-significant coefficients. (e) = easy; (d) = difficult.

suggesting that the difficult fine and gross motor factors were similarly associated with EFs. Additionally, the difficult fine and gross motor factors were correlated to 0.48, suggesting that individual differences in difficult fine and gross motor skills shared about 23% of their variance.

So far, our analyses suggested that the difficult motor task versions were more closely related to EFs than the easy motor task versions. However, the associations between motor tasks and EFs may have been overestimated due to the fact that not all tasks loaded significantly on their intended factors. Additionally, the intercorrelations depicted in the Appendix suggest that performance on the easy and difficult task versions was highly associated. Thus, the separated models probably overestimated the links between the latent constructs even more, due to shared variances with the other task version. Consequently, a final model integrating all included variables and their intercorrelations was indicated.

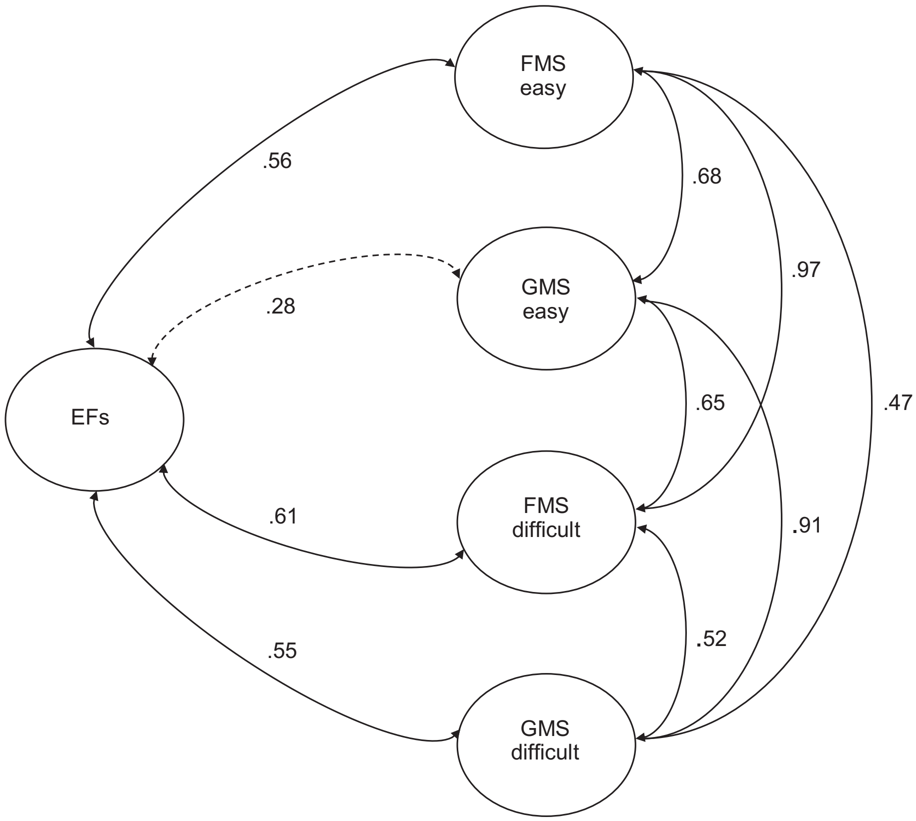

Fig. 2. Final model showing the intercorrelations between all latent factors. Standardized coefficients controlled for chronological age are presented. The dashed path indicates a nonsignificant relation. Only latent constructs and structural paths are presented for clarity. Corresponding factor loadings are shown in Table 3. FMS = Fine motor skills; GMS = Gross motor skills.

Table 3
Factor Loadings of the Indicators on Their Latent Variable of the Model Depicted in Fig. 2.

Latent factor	Indicator	Factor loading
EFs	Flanker	0.32
	Animal Updating	0.58
	Advanced DCCS	0.25
FMS easy	Threading Beads (e)	0.70
	Drawing Trail (e)	0.39
	Posting Coins (e)	0.57
GMS easy	Jumping Sideways (e)	0.51
	Moving Sideways (e)	0.36
	Balance (e)	0.43
FMS difficult	Threading Beads (d)	0.83
	Drawing Trail (d)	0.45
	Posting Coins (d)	0.57
GMS difficult	Jumping Sideways (d)	0.71
	Moving Sideways (d)	0.64
	Balance (d)	*0.20*

Note. EFs = Executive functions; FMS = Fine motor skills; GMS = Gross motor skills; (e) = easy; (d) = difficult; All indicators loaded significantly on their latent factor ($p < .05$), except the Balance (d) task ($p = .055$).

3.3. Final model

We tested the motor–EFs link by examining how performance on EFs and the easy and difficult fine as well as gross motor tasks was related in the present sample. The structural equation model presented in Fig. 2 shows bidirectional associations of all factors.

Factor loadings of each task on their corresponding factors are shown in Table 3. All parameters presented in the model were adjusted for chronological age, with loadings varying between 0.12 and 0.39. The residual variances were allowed to correlate as described above. Additionally, the residuals of each easy and the corresponding difficult task version were allowed to correlate. The fit indices showed that the model fits well with the data: χ^2 (69, N = 124) = 87.5, p = .065, *CFI* = 0.97, *TLI* = 0.96, *RMSEA* = 0.05, *SRMR* = 0.06. The tasks all loaded significantly on their intended latent constructs, except the difficult Balance task (p = .055).

The model depicted in Fig. 2 shows remarkably high correlations between the easy and difficult fine motor factor (0.97) as well as between the easy and difficult gross motor factor (0.91). Thus, one could argue that these correlations suggest that the easy and difficult constructs may overlap to such an extent that their distinction is minimally meaningful. However, constraining the correlation coefficient between the easy and difficult fine motor factor to 1 substantially worsened the model fit, $\Delta\chi^2$ = 15.74, Δdf = 1, $p < .001$. Similarly, a worse model fit resulted when the correlation coefficient between the easy and difficult gross motor tasks was constrained to 1, $\Delta\chi^2$ = 15.28, Δdf = 1, $p < .001$. Consequently, the easy and difficult factors markedly differed from each other and should not be merged.

Moreover, performance on fine and gross motor tasks was strongly associated in the present sample. More specifically, easy and difficult fine as well as gross motor tasks were all significantly intercorrelated with each other, with estimates of correlation coefficients ranging from 0.45 to 0.66. That is, children with high performance on fine motor tasks were also likely to show high performance on gross motor tasks, and those children having difficulties in fine motor tasks also expressed these difficulties with a higher probability in gross motor tasks (and vice versa).

Most importantly, the results displayed remarkably high and statistically significant correlations between both easy and difficult fine motor tasks and EFs. The estimated correlation coefficient between the difficult fine motor tasks and EFs (0.61) was slightly higher as compared to that between the easy fine motor tasks and EFs (0.56). Constraining these two correlations to be equal did not worsen model fit, $\Delta\chi^2$ = 1.84, Δdf = 1, p = .18, suggesting that these two associations did not significantly differ from each other. If we look at the parameters for the paths linking the gross motor tasks to EFs, the results revealed a strong and statistically significant path to the difficult gross motor tasks (0.55) but a non-significant association with the easy gross motor tasks (0.28). That is, performance on the difficult gross motor tasks was strongly related to performance on EFs, but when gross motor demands were low—as assumed to be the case in the easy gross motor tasks—gross motor skills were no longer associated with EFs. Constraining these two correlations to be equal considerably worsened model fit, $\Delta\chi^2$ = 5.5, Δdf = 1, p = .019, suggesting that the link between difficult gross motor skills and EFs differed substantially from the link between easy gross motor skills and EFs.

3.4. Comparing EFs links to easy and difficult motor tasks

Although all EFs tasks loaded significantly on the EFs factor in the final model, the loadings of the Flanker and Advanced DCCS task were rather low. The resulting latent factor used in the analyses reported above may have ignored task-specific, unshared, but yet interesting and relevant EFs processes. In other words, important aspects of EFs performance may be captured in the unshared variances (residuals). To explore the possibility that the structural equation model overestimated the shared processes of motor and EFs tasks, we conducted bivariate and Pearson correlations between performance on the motor and EFs tasks. Thus, in the following analysis, the entire variance stemming from the three EFs tasks was included.

As shown in Table 4, we compared the links of fine and gross motor tasks to EFs as a function of motor task difficulty. For the easy and difficult task versions, respectively, we calculated combined scores including the z-scores of the three respective tasks. It was tested whether the Pearson and partial correlations (controlling for age) between the easy motor tasks and EFs were significantly different from the correlations between the difficult motor tasks and EFs. Results revealed that EFs were not significantly correlated with easy gross motor tasks, r(122) = 0.093, p = .30, but with difficult gross motor tasks, r(122) = 0.279, p = .002. These two dependent correlations differed significantly. This was true for both the partial correlations, $z = -2.712$, p = .007, and the bivariate correlations, $z = -2.497$, p = .013. These results confirmed our findings of the final model and demonstrated that difficult gross motor tasks were more strongly associated with EFs compared to easy gross motor tasks. When testing the links between fine motor tasks and EFs, again, no significant differences between the correlations were found, neither for the partial correlations, $z = -0.726$, p = .468, nor the bivariate correlations, $z = -0.574$, p = .566, indicating that the easy and difficult fine motor tasks were similarly associated with EFs.

Table 4

Pearson Correlations Among Easy and Difficult Fine and Gross Motor Tasks and EFs Below the Diagonal; Partial Correlations Controlling for age Above the Diagonal (N = 124).

		1	2	3	4	5
1	EFs	–	0.321**	0.364**	0.093	0.297**
2	Fine motor tasks (easy)	0.394**	–	0.755**	0.329**	0.343**
3	Fine motor tasks (difficult)	0.425**	0.783**	–	0.346**	0.380**
4	Gross motor tasks (easy)	0.175	0.403**	0.410**	–	0.635**
5	Gross motor tasks (difficult)	0.350**	0.423**	0.446**	0.672**	–

Note: Each easy and difficult fine and gross motor score was built by combining the z-standardized performance scores of the three respective tasks.
*$p < .05$; **$p < .01$ (2-tailed).

4. Discussion

In the present study, we examined the impact of nominal task difficulty of fine and gross motor tasks on the motor–EFs link in typically developing kindergarten children. Results revealed a strong association between performance on motor and EFs tasks in 5- to 6-year-olds. While a substantial link between easy and difficult fine motor tasks and EFs was observed, the study provides new insights into the motor–EFs link by experimentally varying task difficulty.

A key finding of this study was that performance on both easy and difficult fine motor tasks was meaningfully associated with EFs performance. These findings are consistent with previous evidence documenting a significant association between fine motor skills and EFs (Davis et al., 2011; Stöckel & Hughes, 2016; Wassenberg et al., 2005). In comparison to preceding research in 5- to 6-year-olds reporting shared variances ranging from 1.5 to 45% between fine motor skills and EFs (Oberer et al., 2017; Stöckel & Hughes, 2016; but both did not control for age), the present study revealed comparable percentages of shared variances (31% for the easy, 37% for the difficult fine motor tasks). When we did not control for age differences, the proportions of shared variances with EFs were even higher (44% for the easy, 48% for the difficult fine motor tasks, respectively). Thus, in contrast to our expectations, the correlation between the easy fine motor tasks and EFs was similar in magnitude compared to the correlation between the difficult fine motor tasks and EFs. A probable explanation for these almost identical associations is that not only the difficult, but also the easy fine motor tasks were still challenging and cognitively demanding for the participating 5- to 6-year-olds.

The fine motor tasks were challenging in several ways. Posting coins into a slot required attention, an accurate visual perception of the location of both the coin and the slot, precise movements of the hand, and a precise integration of visual and motor information. High demands on fine motor precision to pick up the coins, to navigate the coins to the slot and vertically insert them into the box was needed. Similarly, in the Threading Beads and Drawing Trail task, children were challenged in both the difficult and easy task versions regarding fine motor precision, adaptation of one's behaviour or strategy, and accurate coordination of visual and motor information. Children at this age have not yet practiced their fine motor skills extensively (Case-Smith, Fisher, & Bauer, 1989). Consequently, these fine motor tasks have most likely not yet been automated. To reach automaticity of a certain task or skill, repeated practice is required. It has been shown that the amount of time children spend in different activities has unique effects on children's experiences and cognitive outcomes (e.g., Adolph et al., 2012; Kretch, Franchak, & Adolph, 2014). Children are constantly learning to learn, that is, to adapt to changing environments and body compositions in the context of larger developmental changes (Adolph, 2008). The significant correlations between age and fine motor tasks (see Table in the Appendix) underline that age is a proxy for learning opportunities. Applying this perspective to the results, we are tempted to assume that the involvement of EFs during the execution of both easy and difficult fine motor tasks have been substantial, leading to strong associations with performance on EFs. Our findings thus indicate that not only the demands and challenges of the task itself (nominal task difficulty), but also the developmental and skill level of a child (functional task difficulty) influenced the motor–EFs link.

Concerning the gross motor skills, we found a different pattern in the associations with EFs. Performance on easy and difficult gross motor tasks was differentially related to performance on EFs. While a weak and non-significant correlation was observed between easy gross motor tasks and EFs, the analyses revealed a strong and significant correlation between difficult gross motor tasks and EFs (30% shared variance). These results are compatible with both, a study not finding an association between the two domains considering easy gross motor tasks (Livesey et al., 2006), and results reporting an association when focusing on the difficult gross motor tasks (Oberer et al., 2017). These divergent associations further our understanding of the motor–EFs link and partly explain the inconsistent evidence in the literature. The present findings suggest that the easy gross motor tasks were relatively well learned and cognitively not too demanding. According to Doyon et al. (2009) or Willingham (1998), we assume that in the easy gross motor tasks, even our young participants had already reached the last and autonomous stage of learning a new skill. Automaticity allowed children to perform the easy gross motor tasks with limited demands on EFs (i.e., attentional resources; Seger & Spiering, 2011). Given the non-significant but still positive association between the easy gross motor tasks and EFs, we assume that the required gross motor coordination movements were not yet completely automated. Children in this age probably reached a point of skill development at which EFs were no longer substantially required to perform the tasks (Carlson, Rowe, & Curby, 2013). Therefore, EFs were likely to be minimally involved during performance on the easy gross motor tasks, leading to the weak and non-significant association with EFs.

However, when we confronted children with additional demands on balance, whole-body coordination, and motor planning in the difficult gross motor tasks, performance correlated significantly with EFs. In order to master the increased nominal task difficulty, EFs were needed more. Jumping on the floor, for example, is a familiar, frequent, and mostly automated activity. However, jumping on a highly flexible mat is a less regularly practiced activity. In order to perform this task successfully, children needed to coordinate the whole body, to keep balance, to plan the height and length of each jump, and to constantly adapt to current conditions. Through the experimental manipulation of the nominal task difficulty, we intended to indirectly influence the amount of cognitive engagement in motor tasks, with difficult motor tasks being less automated and therefore involving more EFs than easy motor tasks. Certainly, task difficulty is not a dichotomous variable, but is best understood as a continuous variable.

Besides EFs, there are other candidate processes which provide an explanation for the association between motor and EFs tasks. For example, the instructions of many motor and EFs tasks include to respond as fast as possible without sacrificing accuracy. Individual differences in the ability to master this speed–accuracy trade-off may be one probable explanation. To optimally handle the speed–accuracy trade-off, higher order processes such as planning and monitoring are required. It has been shown that even at this young age, children are able to detect errors and to adapt their speed of responding (for a review see Smulders, Soetens, & van der

Molen, 2016). Studies directly comparing accuracy versus speed-based measures of motor and EFs tasks should further investigate whether mastery of the speed–accuracy trade-off proves a useful explanation for the motor–EFs link.

Another prominent process is the coordination and integration of visual and motor information (e.g., Cameron, Cottone, Murrah, & Grissmer, 2016). In order to perform a task successfully, visual-motor coordination processes were required in all motor and most EFs tasks. Visual-motor coordination skills were needed, for example, to stay inside the boundaries in the Drawing Trail task, to navigate the needle through the hole in the Threading Beads task or to insert the cards into the boxes in the Advanced DCCS task. In almost any motor and EFs task, visual input needs to be combined with a timed motor response. Visual-motor integration is often quantified with the Copy Design task (Beery, Buktenica, & Beery, 2010) in which children are asked to copy different geometric figures. This task includes the ability to visually process the figure, to build a mental representation and to copy that figure, which represents the integration of visual and motor information. In a recent study including preschool and kindergarten children, visual-motor integration yielded the strongest and most consistent associations to EFs (MacDonald et al., 2016). Thus, there is evidence that sensory integration and especially visual-motor integration partly explain the association between motor skills and EFs. However, further studies may aim to narrow down the specific integration processes at work, as most motor tasks require the coordination of visual and motor information simultaneously.

With the present study, we were able to shed light on the nature of the motor–EFs link in 5- to 6-year-old children. The findings revealed that EFs were especially involved in difficult and demanding rather than easy and automated motor tasks. In line with our assumption, findings from neuroimaging studies showed that an increase in cognitive activation in the dorsolateral prefrontal cortex during a cognitive task went along with an increased activation in the contralateral cerebellum (Diamond, 2000). If the neural activation in the prefrontal cortex decreased, especially after training, when less attention was needed to solve the task, the corresponding activation in the contralateral cerebellum decreased concomitantly (Diamond, 2000). In other words, the more automated a motor task becomes, the less involved are EFs. Encouraged by findings of different lines of research and the present study, we conclude that EFs are likely to be more strongly involved in difficult (less automated) than in easy (more automated) motor tasks.

Taken together, the present findings contribute to a better understanding of the nature of the motor–EFs link in healthy 5- to 6-year-old children. By manipulating the nominal task difficulty of the motor tasks, EFs were differentially triggered, leading to a weaker or stronger association with EFs. In contrast to previous studies suggesting that the motor–EFs link is mainly found in the context of fine rather than gross motor skills (e.g., Cameron et al., 2012), the present results demonstrated that not only manual dexterity but also whole-body coordination skills are potentially associated with EFs. If gross motor coordination tasks are demanding (as opposed to automated) depending on the motor developmental and skill level of a child, not only performance on fine but also on gross motor tasks is likely to be related to performance on EFs.

Two features of the present study may limit the conclusions we can draw. Firstly, although we measured motor skills and EFs with a variety of commonly used tasks, these results need to be replicated with different motor and EFs tasks. Especially for measuring EFs in kindergarten children, there is no agreement upon which tasks best capture each single EF component (Baggetta & Alexander, 2016). Secondly, the performance on the easy and difficult task versions significantly differed from each other on the mean performance level. Nevertheless, we cannot exactly circumscribe which aspects in each task increased nominal task difficulty and consequently led to a stronger involvement of EFs. However, the remarkably high interrelations between the easy and difficult task versions (0.91 for the gross motor tasks, 0.97 for the fine motor tasks) suggest that we initiated roughly the same processes in both task versions. Further insights into the aspects of a motor task that trigger EFs and other higher order cognitive processes will improve our understanding of the motor–EFs link.

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Appendix. Pearson Correlations Among the Included Variables (Including age and Gender) Below the Diagonal; Partial Correlations Controlling for age Above the diagonal (N = 124).

Measures	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Age	Gender
1 Flanker	–	0.218*	0.375**	0.163	0.037	0.100	0.194*	0.009	0.164	0.187*	0.202*	0.063	0.159	0.013	0.090	0.189*	0.082
2 Animal Updating	0.249**	–	0.131	0.201*	0.184*	0.181*	0.227*	0.247*	0.317**	0.156	0.254**	−0.062	0.163	0.121	0.273**	0.234**	0.045
3 Advanced DCCS	0.394**	0.178*	–	0.246**	0.060	0.208*	0.423**	0.142	0.228*	0.054	0.010	−0.002	−0.041	−0.139	0.116	0.222*	−0.058
4 Drawing Trail (e)	0.213*	0.247**	0.273**	–	0.592**	0.215*	0.282**	0.350**	0.358**	0.084	0.091	−0.036	0.145	0.124	0.264**	0.259**	−0.116
5 Drawing Trail (d)	0.090	0.233**	0.109	0.624**	–	0.353**	0.288**	0.322**	0.424**	0.120	0.094	0.114	0.083	0.189*	0.323**	0.264**	−0.133
6 Posting Coins (e)	0.135	0.226*	0.251**	0.251**	0.388**	–	0.438**	0.364**	0.515**	0.198*	0.076	0.192*	0.083	0.165	0.216*	0.236**	−0.054
7 Posting Coins (d)	0.210*	0.247**	0.435**	0.296**	0.307**	0.451**	–	0.428**	0.564**	0.197*	0.109	0.091	0.120	0.152	0.228*	0.120	−0.180*
8 Threading Beads (e)	0.073	0.304**	0.203*	0.407**	0.383**	0.411**	0.440**	–	0.638**	0.315**	0.316**	0.223*	0.226*	0.227*	0.141	0.339**	−0.015
9 Threading Beads (d)	0.225*	0.374**	0.285**	0.426**	0.483**	0.548**	0.561**	0.685**	–	0.331**	0.357**	0.225*	0.293**	0.260**	0.263**	0.387**	−0.094
10 Jumping Sideways (e)	0.215*	0.199*	0.102	0.126	0.166	0.240**	0.216*	0.360**	0.377**	–	0.661**	0.138	0.325**	0.233*	0.042	0.215*	0.243**
11 Jumping Sideways (d)	0.247**	0.292**	0.052	0.167	0.159	0.119	0.132	0.369**	0.415**	0.667**	–	0.197*	0.480**	0.272**	0.061	0.228*	0.230*
12 Moving sideways (e)	0.102	−0.004	0.050	0.025	0.167	0.236**	0.116	0.282**	0.290**	0.181*	0.237**	–	0.467**	0.201*	0.046	0.232*	0.131
13 Moving Sideways (d)	0.191*	0.198*	−0.001	0.192*	0.131	0.120	0.139	0.273**	0.339**	0.349**	0.503**	0.488**	–	0.255**	0.107	0.184*	0.074
14 Balance (e)	0.054	0.158	−0.096	0.180*	0.235**	0.197*	0.170	0.275**	0.313**	0.259**	0.311**	0.234**	0.284**	–	0.413**	0.188*	−0.117
15 Balance (d)	0.143	0.323**	0.171	0.326**	0.380**	0.269**	0.251**	0.230*	0.351**	0.102	0.132	0.113	0.158	0.446**	–	0.303**	−0.180*

Note: (e) = easy; (d) = difficult. Gender codes: 1 = girls; 2 = boys. $^{*}p < .05$; $^{**}p < .01$ (2-tailed).

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